

APPLICATION FOR UNITED STATES PATENT

FOR

**REGULATING VOLTAGE APPLIED TO AN INTEGRATED CIRCUIT
AND PROXY FREQUENCY**

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TECHNICAL FIELD & BACKGROUND

The present invention is related to the field of integrated circuits. More specifically, various aspects of the present invention are related to the detection 5 of the potential of the operational frequency of an integrated circuit, and regulation of voltage applied to the integrated circuit, based at least in part on the detection.

Advances in integrated circuit (IC) technology have led to significant increases in the operational frequencies of IC. Typically, a manufacturer of an IC 10 designs and guarantees the IC to operate properly up to a specification maximum operational frequency, if voltage supplied to the IC is within a targeted voltage range. Generally, to reduce power consumption, it is desirable to operate the IC near the lower end of the targeted voltage range.

In addition to being dependent on the applied voltage, the operational 15 frequency of an IC may also be dependent at least in part on the temperature of the IC, the age of the IC, and/or other factors. Thus, various environmental limits, such as, but not limited to, temperature, voltage and so forth, are specified to facilitate a system designer to manage the usage of the IC, to ensure it functions properly. These environmental limits are typically conservatively 20 specified (guardbanded) to accommodate among other things, aging of the IC. The level of conservatism (or magnitude of the guardband) varies from manufacturer to manufacturer, depending in part on the quality experience of the manufacturer.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be described by way of exemplary embodiments, but not limitations, illustrated in the accompanying drawings in which like references denote similar elements, and in which:

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Figure 1 illustrates a block diagram of an integrated circuit, in accordance with one embodiment of the present invention;

Figure 2 illustrates the monitor of the voltage regulator controller **Fig. 1** in further detail, in accordance with one embodiment;

10 **Figure 3** illustrates the monitor of the voltage regulator controller of **Fig. 1** in further detail, in accordance with another embodiment; and

Figure 4 illustrates a system having the IC of **Fig. 1** in accordance with one embodiment.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

Embodiments of the present invention include, but are not limited to, an IC having operational circuits and a proxy circuit to output a periodic signal (proxy signal) at a frequency (proxy frequency) reflective of a potential of the operational frequency of the operational circuits, a voltage regulator controller integrated or associated with the IC to regulate voltage applied to the IC based at least in part on the proxy signal provided by the proxy circuit, and a system having such an IC.

Various aspects of the illustrative embodiments will be described using terms commonly employed by those skilled in the art to convey the substance of their work to others skilled in the art. However, it will be apparent to those skilled in the art that the present invention may be practiced with only some of the described aspects. For purposes of explanation, specific numbers, materials and configurations are set forth in order to provide a thorough understanding of the illustrative embodiments. However, it will be apparent to one skilled in the art that the present invention may be practiced without the specific details. In other instances, well-known features are omitted or simplified in order not to obscure the illustrative embodiments.

Various operations will be described as multiple discrete operations, in turn, in a manner that is most helpful in understanding the present invention, however, the order of description should not be construed as to imply that these operations are necessarily order dependent. In particular, these operations need not be performed in the order of presentation.

The phrase "in one embodiment" is used repeatedly. The phrase generally does not refer to the same embodiment, however, it may. The terms

"comprising", "having" and "including" are synonymous, unless the context dictates otherwise.

Referring now to **Fig. 1**, wherein a block diagram view of an IC in accordance with one embodiment, is shown. As illustrated, **IC 100** receives its current supply from voltage/current source **110**. **IC 100** includes a number of operational circuits (not shown). Further, **IC 100** advantageously includes proxy circuit **102** (which also draws current from the same source **110**). For the illustrated embodiment, **IC 100** also includes control parameter storage **106** and light weight voltage regulator controller **112**. The illustrated elements are coupled to each as shown.

Operational circuits are employed to provide the functions **IC 100** is designed to offer. The functions, and therefore, operational circuits are application dependent, and the application may be of any kind. In one embodiment, **IC 100** implements a general purpose microprocessor. In other embodiments, **IC 100** may be a graphics processor, a network processor, other application specific integrated circuits (ASIC), or a reconfigurable integrated circuit, such as, but not limited to, Field Programmable Gate Array (FPGA) and so forth.

Proxy circuit **102** is employed to generate a periodic signal (proxy signal) at a frequency (proxy frequency) that is reflective of a potential of the operational frequency of an operational portion of **IC 100** of interest (hereinafter, the constituent operational circuit). Recall that the operational frequency is dependent at least in part on the voltage applied, the temperature, and the age of an IC, accordingly, in various embodiments, proxy circuit **102** may be formed at a location of the IC that is near the constituent operational circuit, which operational frequency potential is to be reflected. Such proximal placement allows proxy

circuit **102** to substantially experience the same process variations in its formation, as well as ambient influences during operation, as the constituent operational circuit which operational frequency it is to reflect. However, in other applications, for other reasons, proxy circuit **102** need not be so proximally placed.

In various embodiments, proxy circuit **102** is a ring oscillator, which on application of power, continuously generates a periodic signal (proxy signal) at a frequency (proxy frequency). The oscillator toggles per unit time is a measure of frequency. The number of stages or the length of the ring oscillator is implementation dependent. In particular, it may be dependent on the manner the oscillator's frequency is measured. In alternate embodiments, other periodic signal generation circuits may be employed. Further, it is anticipated that in some embodiments, proxy circuit **112** may have configurable elements, to allow customization of the characteristics of the proxy signal.

Light weight voltage regulator controller **112** is employed to conditionally regulate the voltage applied to IC **100** by source **110**, based at least in part on the potential of the operational frequency of all or a subset of the operational circuit(s) of IC **100**, as reflected by the proxy frequency of the proxy signal. For the illustrated embodiment, voltage regulator controller **112** includes monitor **104** and control block **108**, coupled to each other as shown. Voltage regulator controller **112** is referred to as light weight, because for the intended usage, it is not necessary for voltage regulator controller **112** to include elements, such as inductors, bulk caps, and so forth.

For the embodiment, monitor **104** is employed to detect the difference between the proxy frequency and a target of the proxy frequency. The target of the proxy frequency is typically determined at manufacturing time, or more

specifically, quality testing time, when the specification maximum of the operational frequency of the constituent operational circuit is determined. The specification maximum of the operational frequency of the constituent operational circuit at a particular temperature, may be determined e.g. through a binary

5 search, while IC 100 is held at the particular temperature. The search may also be conducted employing a voltage reference. Typically, the searches are conducted for a number of temperatures in a temperature range. Other methods may also be employed to determine the specification maximum of the operational frequency. Couple of embodiments of monitor 104 will be described later,

10 referencing **Fig. 2-3.**

As will be readily apparent from the descriptions to follow, in alternate embodiments, the responsibilities of monitor 104 may be more or less. That is, in these alternate embodiments, some of the responsibilities of monitor 104 may be "pushed out" to control block 108, or vice versa. That is, the demarcation 15 between monitor 104 and control block 106 is partially arbitrarily, and implementation dependent.

For the embodiment, control block 108 is employed to generate control signals for source 110, based at least in part on the outputs of monitor 104. In various embodiments, the control signals control the pulse widths of various 20 transistors employed by source 110 in generating current for IC 100.

In general, control block 108 is employed to generate control signals to decrease the voltage applied to IC 100 if the potential of the operational frequency of the constituent operational portion of IC 100 is believed to be higher than its target operational frequency, and to generate control signals to increase 25 the voltage applied to IC 100 if the potential of the operational frequency of the

constituent operational portion of IC **100** is believed to be lower than its target operational frequency.

Further, the amount of increase/decrease is in general a function of the amount of difference detected for the proxy frequency and its target (which may 5 be selected based on a target maximum operational frequency for the constituent operational circuit). However, other factors, such as temperature of IC **100**, age of IC **100**, as well as precision desired (i.e. granularity of control), may be taken into consideration, in generating the control signals to increase or decrease the voltage and/or current applied. The functional relationship between the 10 adjustment to be undertaken and the factors to be considered, may be linear or non-linear, depending substantially on the design and usage characteristics of IC **100**, and it is typically, though not necessarily, empirically determined.

In various embodiments, depending on the sophistication of the models, and therefore, the complexity of the "calculations" required to generate the 15 control signals, control block **108** may be implemented with a relatively simple to a relatively complex circuit, including, but not limited to, a collection of gates configured with combinatorial logic, or a general purpose microcontroller programmed with control logic.

For the embodiment, control parameter storage **106** is employed to store 20 various control parameters. In particular, for the embodiment, it is employed to store the target proxy frequency of the constituent operational portion of IC **100**, and various control values to control the operation of voltage regulator controller **112**, in particular, monitor **104**. In various embodiments, the stored control parameters may also include an upward adjustment as well as a downward 25 adjustment to the target proxy frequency of the proxy circuit, to be described more fully below.

In various embodiments, control parameter storage **106** may be implemented employing non-volatile storage, such as read-only-memory (ROM), electrically erasable ROM (EEPROM), flash memory, and so forth, and/or fuses, i.e.. a combination thereof. In other embodiments, control parameter storage **106** 5 may also be implemented employing volatile storage, such as random access memory (RAM) if facilities to save to, and restore from a persistent store of a host device hosting IC **100** are also provided.

Source **110** typically includes a number of transistors, diodes, inductors, capacitors and/or resistors coupled to one another to provide a voltage/current 10 output. Source **110** may be a voltage/current supply of any kind, as long as it is able to meet the voltage and/or current requirement of IC **100**, and includes an interface to allow its output voltage to be controlled by control block **108** by controlling e.g. one or more of its transistors.

Resultantly, by virtue of the ability to reliably estimate the operational 15 frequency potential achievable by the operational circuits, and adjust the voltage applied to IC **100** accordingly, it is expected that the specification maximum operational frequency may be achieved with voltage near the lower end of the design voltage range. Thus, it is expected that the specification maximum operational frequency is likely to increase, but at the same time, there will be 20 substantial power savings.

Further, in various embodiments, control parameter storage **106** may also be employed to store various environmental limits to be monitored and managed, to ensure the proper operation of IC **100**. Examples of environmental limits include, but are not limited to various critical temperature limits, nominal 25 maximum operational frequency, minimum and maximum voltage, and so forth. These environmental limits are employed by light weight voltage regulator

controller **112** and/or various off-chip system management facilities to manage the operation of a host system, of which IC **100** is a component. From the description to follow, it will be appreciated by those of ordinary skill in the art, that by virtue of the novel features and methods of the present invention, typically,
5 these environmental limits may be set more aggressively to “lower” limits. It is expected that employment of various embodiments of the present invention will likely lead to significant reduction in all or selected ones of the typical environmental limits.

Additionally, IC **100** may also include a special mode of operation for the
10 above described calibration and determination of the specification maximum operational frequency (including the target for the proxy frequency), and a number of environmental factor sensors or circuits, such as, but not limited to, voltage sensors, temperature sensors, and so forth, as well as an input terminal for the provision of voltage references, to facilitate the calibration and
15 determination.

While for ease of understanding, voltage regulator controller **112** (with monitor **104** and control block **108**) and control parameter storage **106** are being illustrated as part of IC **100**, in alternate embodiments, one or more of these elements or sub-elements may be located off chip, on e.g. a circuit board, to
20 which IC **100** is mounted.

Further, while also for ease of understanding, only one proxy circuit **102** is shown, in alternate embodiment, IC **100** may employ multiple proxy circuits **102**, one each for different constituent regions. For these embodiments, voltage regulator controller **112** (with monitor **104** and control block **108**) and control
25 parameter storage **106** may be modified to cooperate with the multiple proxy

circuits **102** (e.g. interleavingly), or multiple sets of these resources, one for each proxy circuit **102** may be provided instead.

Figure 2 illustrates monitor **104** of voltage regulator controller **112** of Fig. 1 in further detail, in accordance with one embodiment. As illustrated, for the 5 embodiment, monitor **104** includes counters **202-204**, divider **206**, synchronizer **208**, register **210**, and comparator **212**, coupled to each other, proxy circuit **102**, and control parameter storage **106** as shown.

Comparator **212** is employed to receive the determined proxy frequency, i.e. frequency of the proxy signal outputted by proxy circuit **102**, (from register 10 **210**), and a target of the proxy frequency (from control parameter storage **106**), and in response, generates an output indicating the difference between the two frequencies.

Counter **204** is employed to sample the proxy signal for a period of time, or more specifically, for the embodiment, a derived version of the proxy signal 15 **213**, to determine the frequency of the proxy signal, which as described earlier, is considered reflective of a potential of the operational frequency of the constituent operational circuit(s) of IC **100**. Counter **204** includes in particular an input terminal to receive the derived version of the proxy signal **223**, which is aligned with the operational cycles of the constituent operational circuit(s), to be 20 described more fully below. Counter **204** further includes a “clear” (CLR) input terminal to receive control signal **220** to periodically clear it, to effectively control the start and stop of sampling (counting) for each time period. Counter **204** further outputs the determined proxy frequency for register **210**.

Register **210** is employed to store the determined proxy frequency. 25 Register **210** includes an input terminal to allow the same control signal **220** to be provided to control register **210** to latch the determined proxy frequency

outputted by counter **204** at the end of a sampling period, synchronous to the time when counter **204** is being cleared to start sampling for a new time period, and to output a stored determined proxy frequency for comparator **212**.

For the embodiment, divider **206** is employed to divide the periodic signal 5 received from proxy circuit **102** to generate a derived version of the periodic signal **221**. Typically, this derived version of the periodic signal **221** is not aligned with the operational cycles of the constituent operational circuit(s) of IC **100**.

The terms "alignment" or "aligned" as used herein in the specification, and 10 in the claims, refer to edges of the signal pulses being aligned, i.e. they substantially rise and fall together (in phase or phase shifted), but not necessary of the same frequencies. For example, for the purpose of this specification and the claims, a signal with a 200MHz frequency and a signal with a 100MHz are considered aligned, if the edges of the pulses of the slower 100MHz signal 15 substantially rise and fall with every other edges of the pulses of the twice as fast 200MHz signal (in phase or phase shifted).

Synchronizer **208** is employed to align the derived version of the proxy signal **221** with the operational cycles of the constituent operational circuit(s) of IC **100**, and output the aligned version as derived version **223** to counter **204**.
20 Thus, synchronizer **208** receives the derived version **221** from divider **206**, and clock signal (CLK) **224** as inputs. CLK **224** is a clock signal with a frequency that is either the same or a multiple of the frequency of the clock signal employed to drive the constituent operational circuit(s) (in phase or phase shifted). In other words, as an example, if a clock signal with a 800MHz frequency is employed to 25 generate a clock signal of 400MHz for the constituent operational circuit(s), CLK

224 may be a clock signal with a frequency of either 800 MHZ or 400 MHZ (in phase or phase shifted).

Counter **202** is employed to generate control signal **222**. Counter **202** receives the same clock signal CLK as input, and counts accordingly. Counter **202** outputs its count as control signal **222**.

While the embodiment of **Fig. 2** employs counter **204** to determine the frequency of the proxy periodic signal outputted by proxy circuit **102**, in alternate embodiments, the frequency of the proxy periodic signal may be determined via other approaches. For example, an implementation with proxy circuit **102** having an m stage oscillator, and counter **204** counting up to n cycles, may also be implemented with proxy circuit **102** having m x n stages, with the proxy frequency being determined based on the amount of delay incurred by a signal traversing through the m x n stages.

Figure 3 illustrates monitor **104** of **Fig. 1** in further detail, in accordance with another embodiment. The embodiment of **Figure 3** is substantially the same as the embodiment earlier described referencing **Fig. 2**, except that comparator **212** is enhanced to also receive one or more adjustments to the target of the proxy frequency to be taken into consideration when generating the difference between the determined proxy frequency and its target.

In various embodiments, the adjustments include an upward adjustment and a downward adjustment. The adjustments provide a manufacturer of IC **100** with a number of flexibilities in marketing the IC. For example, the upward adjustment may be employed to market IC **100** as a part with a lower specification maximum operational frequency, even though during production, it was tested and confirmed to be capable of operating reliably with a higher unadjusted specification maximum operational frequency. Presumably, IC **100**

will be marketed with a downward price adjustment when compared to other IC marketed for operation with the higher unadjusted specification maximum operational frequency. However, subsequently, the downward adjustments may be employed to field upgrade IC 100 to operate with a higher specification

5 maximum operational frequency, which could be as high as the original higher unadjusted specification maximum operational frequency or lower (reflecting the part's age), depending e.g. on the amount of an upgrade payment received. This is just one of many possible applications of the various embodiments of the present invention.

10 In alternate embodiments, comparator 212 may be merely enhanced to accept only one adjustment to the target proxy frequency. In other words, the adjustments are all summed into a net adjustment, before it is provided to comparator 212.

15 Note that for the same reason, the earlier described application may be practiced with the embodiment of **Fig. 2** if all adjustments are factored into the target proxy frequency before it is provided to comparator 212.

In other words, similar to the earlier description of the demarcation between monitor 104 and control block 108 need not be as described, and may move in either direction with monitor 104 assuming some of the functions of 20 control block 108 or vice versa, likewise, the demarcation between control parameter storage 106 and monitor 104 need not be as described either, and may move in either direction with control parameter storage 106 assuming some of the functions of monitor 104 (in particular, comparator 212), or vice versa.

Figure 4 illustrates a system in accordance with one embodiment. As 25 illustrated, for the embodiment, system 400 includes microprocessor 402, memory 404, and networking interface 406 coupled to each other, via bus 408.

For the embodiment, microprocessor **402** is advantageously equipped with proxy circuit **102**, voltage regulator controller **112** (with monitor **104** and control block **108**) and control parameter storage **106**, as early described for IC **100**.

Accordingly, the voltage applied to microprocessor **402** may be adjusted in view
5 of the operational frequency microprocessor **402** is believed to be capable of,
based on the experience of proxy circuit **102**.

Beside the advantageous incorporation of elements **102**, **106** and **112**,
microprocessor **402**, memory **404**, networking interface **406** and bus **408** all
represent corresponding broad ranges of these elements known in the art or to
10 be designed. Further, as described earlier, in alternate embodiments, all or
portions of voltage regulator controller **112** may be disposed outside
microprocessor **402**.

Depending on the applications, system **400** may include other
components, including but are not limited to non-volatile memory, mass storage
15 (such as hard disk, compact disk (CD), digital versatile disk (DVD) and so forth),
graphical or mathematic co-processors, and so forth.

In various embodiments, system **400** may be a personal digital assistant
(PDA), a wireless mobile phone, a tablet computing device, a laptop computing
device, a desktop computing device, a set-top box, an entertainment control unit,
20 a digital camera, a digital video recorder, a CD player, a DVD player, or other
digital device of the like.

Further, in various applications, system **400** may have multiple
microprocessors having integrated or associated voltage regulator controllers as
earlier described. Moreover, the multiple microprocessors may be multiple
25 processor cores integrated on the same die.

Conclusion and Epilogue

Thus, it can be seen from the above descriptions, a novel apparatus with the ability to regulate the voltage applied to an IC, based on the operational frequency it is believed to be capable of, per its proxy circuit, method for 5 performing the detection and regulation, and a system having such an IC have been described. While the present invention has been described in terms of the foregoing embodiments, those skilled in the art will recognize that the invention is not limited to the embodiments described. The present invention can be practiced with modification and alteration within the spirit and scope of the 10 appended claims.

Thus, the description is to be regarded as illustrative instead of restrictive on the present invention.